Principles and characteristics of FETs

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THE field-effect device was first described in 1952 by W. Shockley, co-inventor of the better known bipolar transistor. Since then, the advantages of the fet over the bipolar device have been recognized and exploited and, while it would be wrong to say that the fet could usurp the bipolar transistor, there are many small-signal applications in which the fet is decidedly superior. The two main advantages of the fet over the bipolar transistor, as will be explained later, are a far greater input resistance and a superior noise performance.

Construction and operation

A schematic view of a fet is shown in Fig 1. The device consists of a block of n-type semiconductor material, known as the channel, into which is diffused a p-type region known as the gate. Ohmic (non-rectifying) connections are made to the ends of the channel and to the gate region. These are known as the source, gate and drain connections. Fig 2 shows a sectional view through the device in the plane of the three connections alongside the most widely-used circuit symbol for the fet.

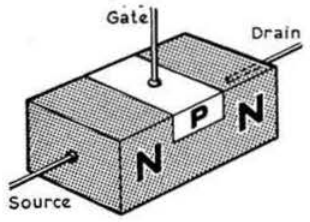

Fig 1. Schematic view of a fet

The n-type channel and the p-type gate region form a pn junction and a depletion layer is naturally formed. If the gate is made negative with respect to the source the gate-channel junction will be reverse-biased and the depletion layer will grow, since a greater voltage will be capable of sweeping away a larger number of charge carriers. The depletion layer will spread into the channel as the gate source voltage is increased until, at a reverse-bias voltage known as the pinch-off voltage (denoted by V_p), the entire width of the channel will be occupied by the depletion region.

Imagine that there is zero gate-source bias (gate and source terminals connected together) and a voltage is applied between the drain and the source so that the drain is made positive. The n-type material of which the channel is composed is of fairly high conductivity and a current of perhaps 15mA (for, say, 10V drain-source voltage) will flow. One might suppose that the channel would act as a simple resistance but this is not the case, as will be explained later.

Now consider the effect of reverse-biasing the gate-channel junction by making the gate-source voltage negative. The depletion layer will expand and restrict the flow of current through the channel. Thus, as the gate-source voltage increases in the negative direction, the drain current decreases. Because the gate-channel junction is reverse-biased it presents a very high resistance to a signal applied between source and gate, and the gate current will be very small, typically a few tens of nanoamps. Therefore a useful current may be controlled by a voltage source from which a negligible current will be drawn. In more practical terms, if the device is used as an amplifier it will have a very high input resistance.

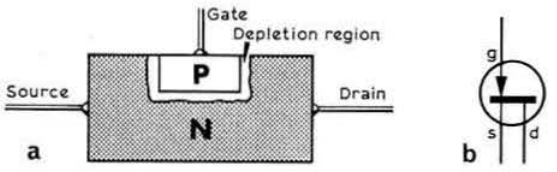

Fig 2. Section through the device of Fig 1, and circuit symbol

Characteristics

Fig 3 shows the relationship between drain-source voltage and drain current for a fet with zero gate-source bias. The drain-source voltage is denoted by V_{ds} and the drain current by I_d. As may be seen from the figure, the drain current is proportional to the applied voltage over a very small range of voltage only (V_{ds} less than 3 or 4V). Beyond this limited range the current levels out to an approximately constant value. The reason for this is that, even with zero gate-source voltage, the depletion region will spread into the channel when drain current flows because the gate-channel junction is reverse-biased by the voltage dropped along the length of the channel between gate and source. Since the gate-source voltage is fixed at zero, greater spreading of the depletion region will occur at the drain end of the channel as shown in Fig 4. Eventually a point is reached beyond which any attempt to increase the current flowing is neutralized by an increase in the size of the depletion region. The net effect is that for drain-source voltages greater than a few volts, the drain current is approximately constant. The saturation value of drain current, with zero gate-source voltage, is denoted by I_{dss}. A more detailed analysis will show that the drain current is approximately constant for values of V_{ds} beyond the pinch-off voltage (referred to earlier) which may be 3 or 4V.

As might be expected, the effect of a negative gate-source voltage is to decrease the "saturation" value of I_d. This

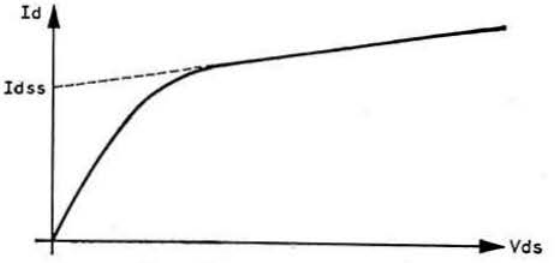

Fig 3. Graph of V_{ds} against I_d

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saturation effect should not be confused with saturation in bipolar transistors, which is completely different in both cause and effect. Fig 6 shows the relationship between V_{gs} and I_d for a fixed value of V_{ds} greater than V_p. As may be seen, the rate of decrease of I_d with V_{gs} is approximately constant for values of V_{gs} less than V_p. This rate of change is denoted by g_m and is called the mutual conductance of the device. Because g_m does vary slightly with V_{gs}, data sheets usually quote g_{mo}, the value of g_m with $V_{gs} = 0$.

Several points must now be made clear. First, there are no objections in principle to making the drain of a fet negative with respect to the source, so that the drain current is made to flow in the opposite direction to that in which we have so far assumed it to flow. However, it is simpler to call one terminal the source and the other the drain, and assume the charge carriers to leave the former and travel to the latter, than to regard the two as interchangeable. Second, the gate is always held more negative than the source, for the obvious reason that if the gate-channel junction were to become forward-biased a fairly large current would flow in the gate terminal, the input resistance would drop and serious distortion of an amplified signal would occur. The third point that should be made is that the region of Fig 3 in which the drain current is constant is often referred to as the pinch-off region, although, strictly speaking, pinch-off occurs only when the channel is completely blocked by the depletion region and the drain current is zero.

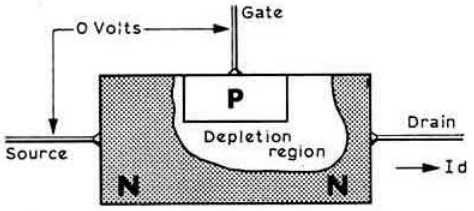

Fig 4. When drain current is flowing, the depletion region will spread into the channel even at zero gate source voltage

The fet, then, is a device in which a very small current (the gate current) controls a much larger one (the drain current). In other words, the device has current gain and may be used as an amplifier. There are two types of fet: the most common is the junction fet which has been described here, but there is also a device known as the mosfet in which a metal gate is insulated from the channel by a very thin layer of insulating material. But there are further complications, for there are two types of junction fet. There is the n-channel device, described here and so named for obvious reasons, and there is the complementary p-channel device in which the channel is composed of p-type material and the polarities of the applied voltages are reversed.

At present, p-channel devices are about twice as expensive as n-channel devices of comparable performance.

Applications

It is painfully evident from the manufacturer's data sheet for any typical fet that the possible spread in characteristics between individual specimens of a particular device can be very large. Indeed, the only difference between an expensive device and a cheap one will often be that the expensive one has a smaller guaranteed spread of characteristics. It has already been said that a fet used as an amplifier will generally

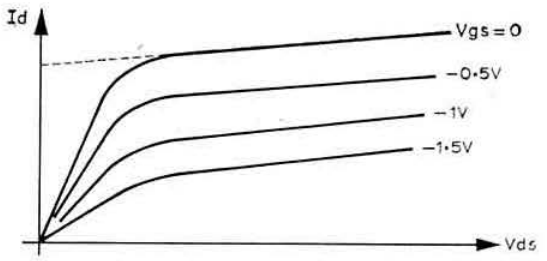

Fig 5. Graph of V_{ds} against I_d for negative values of V_{gs}

have a much larger input resistance than a bipolar transistor. The other great advantage of the fet is that it generates less noise than the bipolar transistor. The reason for this is that the operation of the fet relies on the control of majority carrier flow in the channel, whereas the bipolar transistor relies on the injection of minority carriers into the base region.

In the fet, the controlled current flows along a long, thin channel of semiconductor material, while in the bipolar transistor it flows across a short, broad base region. For this reason it is not convenient to produce FETs that can conduct as much current, and therefore handle as much power, as a bipolar power transistor. This limits the fet to small-signal applications and means that the bipolar transistor still reigns supreme in the realm of power amplifier stages.

With these advantages and disadvantages in mind, let us consider to what use we can put FETs. The most obvious application is a small-signal amplifier with a high input impedance, for example as a preamplifier for a crystal microphone or a ceramic pickup. The biasing method employed for FETs is, as a rule, similar to that employed for valves. For normal operation, the gate must be made more negative than the source and the gate-source voltage must bias the device to a linear part of the $V_{gs} - I_d$ curve (such as point P in Fig 6). Clearly it would be inconvenient to connect the source to ground and have a negative supply line of just a few volts, in addition to the positive supply line of perhaps 12V, simply to satisfy the bias requirements of the one device. What is normally done is to connect the gate to ground through a very large resistance (there will be zero voltage drop across this resistance, since the gate current is negligible) and make the source the requisite number of volts positive with respect to ground. The way this is done is illustrated in Fig 7, which is the circuit of a small-signal fet amplifier. The source current of several milliamps flowing through R_S results in a voltage drop which makes the source positive with respect to earth.

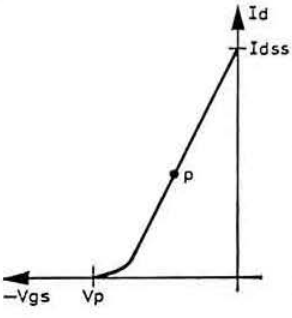

Fig 6. Graph of V_{gs} against I_d for constant V_{ds} greater than V_p

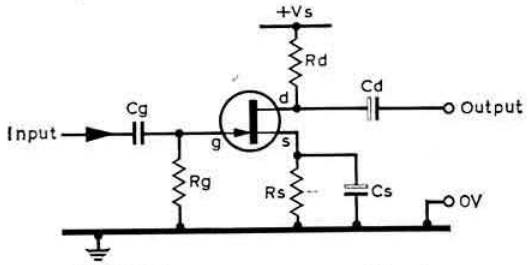

Fig 7. FET common source amplifier stage

There are two good points about this method of biasing (apart from its simplicity). First, if the source current were to rise or fall unintentionally because of a change in temperature, for example, the consequent change of source voltage will be of the correct polarity to restore the status quo by increasing the bias voltage. The circuit is to a certain extent, therefore, self-stabilizing. Second, the input is at ground potential, if we ignore C_g, which is an advantage in some applications. R_d in Fig 7 is adjusted so that the voltage of the drain is approximately midway between that of the source and the supply voltage, thus giving the stage the maximum possible output voltage swing.

The stabilizing action of the source resistor, properly considered, is a form of negative feedback. The purpose of the capacitor in parallel with the source resistor is to ground the source from the point of view of signals so that negative feedback at signal frequencies, which would reduce the gain of the stage, cannot occur. C_g and C_d serve simply as dc blocking capacitors. The configuration in Fig 7 is known as the common source configuration, since both the output and the input are connected, through C_s, to the source. As one might guess, there also exist a common gate configuration and a source follower. The circuit configuration of Fig 7 may be used successfully at audio frequencies, but will be almost useless at rf because of the Miller effect. This limitation may be overcome by using a cascode configuration (as with valves), by using a dual-gate mosfet or by neutralizing the drain-gate capacitance.

Returning to the circuit of Fig 7, if we call the drain current I_d and the supply voltage V_s we have:

$$R_s = \frac{I_{dss} - I_d}{g_{mo}\, I_d} \text{ and } R_d = \frac{V_s}{2I_d}$$

Voltage gain $= g_{mo}\, R_d$. Output resistance $= R_d$.

Typically, the drain current would be between 1 and 5mA and the gate resistor R_g would be of the order of 1MΩ. The foregoing assumes that the decrease in drain current is proportional to the gate-source bias, in other words that the mutual conductance is constant. In fact this is not exactly the case, although the above formulas are sufficiently accurate for most practical applications.

In the fet, the current flowing along the channel at a particular drain-source voltage is controlled by the gate-source bias. In this sense, the fet can be regarded as a voltage-controlled variable resistance, the "resistance" of the channel being controlled by the voltage applied between gate and source. Of course some care is needed when speaking of the "resistance" of the channel because, as we have seen, the relationship between drain current and drain-source voltage is non-linear. Thus, a fet may be used, for example, as a high-speed switch or as a means of controlling the gain of an amplifier in a speech compressor. Because the reverse-biased gate-channel junction represents a very high resistance, the fet will draw very little current from the controlling signal.

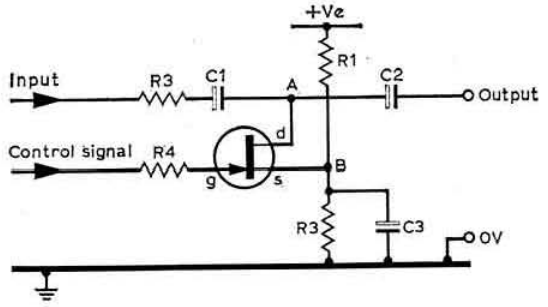

Fig 8. A fet used as a voltage-controlled attenuator

A typical practical arrangement is shown in Fig 8. The values of R1 and R2 are arranged so that when the control voltage is at ground the channel is just pinched off and the effective resistance between points A and B is infinite. By increasing the control voltage the reverse bias is made less and less and the effective resistance between A and B is decreased. Therefore, the attenuation of the circuit is controlled by a small voltage applied to the gate and we have a fast-acting variable attenuator with no moving parts. Because the channel behaves non-linearly, some care must be taken in using a fet as a voltage-controlled resistance to ensure that the controlled signal does not suffer distortion.

Conclusions

That, then, is the field-effect transistor. This is intended merely as an introductory article, and more detailed information can be obtained elsewhere. We have said very little about the insulated-gate MOSFETS which are even more versatile than the junction devices and even nearer in circuit design terms to the valve. The fet should not be considered as an opponent to the bipolar transistor, but rather as a complementary device with many advantages not possessed by the bipolar transistor, though lacking some of the good points of the earlier device.

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